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BATTERY ACTUATION OF NITINOL AT SUB-ZERO TEMPERATURES

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RESEARCH AND TECHNOLOGY DEPARTMENT

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It is feasible to use batteries to produce rapid shape memory response in NITINOL wires which are in sub-zero temperature ambients. Data are presented on lithium thionyl chloride batteries used to joule heat 10 mil diameter wires of nominal transformation temperatures of 90-105°C. The batteries and wires were jointly tested in a -35°C ambient air environment. The wire contracted 5 percent in length (0.4 inch) and lifted a 1 pound load in ½ second.

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FOREWORD

The shape memory alloy NITINOL was investigated for use as the active element of a Safing and Arming subsystem of a fuze. A prior NSWC study presented data on shape recovery, as triggered by a power supply starting from a room temperature ambient. This study considers starting from a -35°C ambient and triggering from batteries which are also at the same sub-zero temperature.

The author gratefully acknowledges the significant assistance of Messrs. Dan Lenko, John Scarzello, and Gary Burak in advancing our capability to reach our objective. Messrs. Roy Davis and Ed Morai were most helpful in setting up the successful test procedure.

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BACKGROUND

Alternate methods of activating weapons related devices in hostile environments may have special advantages for remote or unattended military operations. NITINOL shape memory alloys, which can directly convert electrical into mechanical energy, offer one such alternate. Timing the actuation of NITINOL can be done by electronic circuitry, while heating it can be done by battery pulses. When heated, NITINOL generates substantial forces and motions as the result of a crystal transformation.

Reference 1 presented data on power supply actuation of a NITINOL wire with an ambient starting temperature of 20°C. The current work considers the capability of a wire and batteries, both at -35°C, to be the active elements of a small size actuator.

INTRODUCTION

A NITINOL alloy exerts stresses on the order of 50 ksi (350 MPa) when it transforms from its low temperature (martensitic) crystal structure to its higher temperature (austenitic) structure. Transformation ordinarily occurs at 150°C or lower. If the NITINOL is in wire form it will also contract 6 percent of its length while exerting the 50 ksi force. This contraction is a variant of the shape memory phenomenon, i.e., it is a change in length rather than shape. The temperature range of the transformation is a function of alloy composition, prior heat treatment, and strain.

The high electrical resistance of NITINOL, about 40 times that of copper, makes joule (resistance) heating an attractive method of producing transformation. Small capacitors or batteries with sufficient stored energy will enable NITINOL-based devices to be both portable and suitable for delayed, unattended, or remote operation in adverse environments.

The limiting conditions to applications of battery operated devices include low ambient temperatures, acceptable total weight and volume, and suitable work output of the NITINOL. For some military or space applications, shock, vibration, and fail-safe conditions may also be limiting. Reasonable values of these constraints are within the capabilities of NITINOL and the batteries used in this experimental work. In this work, the performance of batteries at -35°C and a NITINOL temperature excursion from -35°C to about 120°C are specified as the operating conditions.

EXPERIMENTAL PROCEDURES

The NITINOL wire test specimens were taken from Heat 83825, of the same lot used in Reference 1. They were cold drawn to 10 mils (1/4mm) diameter and heat treated at 375°C for 1/2 hour, followed by air cooling.

Test specimens were lightly abraded at their ends and copper sleeves were crimp attached. The wire length between the crimp sleeves, approximately 8 inches (20 cm), was measured with a steel rule with 1/64th-inch graduations, using optical magnifiers. Errors in the gauged length between the shoulders of the sleeves were estimated to be less than 0.1 percent. The wires were chilled to -5°C to ensure that they would martensitically deform upon the subsequent 6 percent stretching at room temperature. After stretching, the wires were stored at room temperature until tested. Spot checks on their lengths were performed at random after one week, with only minor random variations found in as-stretched length. Typically, the resistance of each wire increased from an initial value of 3.0 to 3.7 ohm following stretching.

Stainless steel wire loops were crimped into the free end of each copper sleeve. These steel loops were connected respectively to a fixed wall and to a movable hanging weight and a dial gauge, as shown in Figure 1. The latter measured the contraction of the NITINOL during electrical pulsing. The copper crimp sleeves were also the contact points for electrical heating and for measurement of voltage drop.

Commercially available batteries were used as the energy source for the electrical resistance heating. They were external to the controlled temperature chamber in preliminary tests, but were equilibrated in the test chamber for four hours before the low temperature tests.

The contraction of the wire and voltage drop during pulsing were observed on the dial gauge and on a digital voltmeter. Pulses as short as 0.5 second could be monitored with assurance. The values reported in Table 1 are not precise, but their magnitudes clearly indicated complete vs. incomplete transformations.

The decreasing values of open circuit voltage shown for the sequential tests are due to intentional re-use of the same batteries, simulating field conditions. Virgin wires were used for each test since first time transformations of NITINOL can require higher temperatures than subsequent ones.[2] The procedure of using virgin wires satisfies possible designs for actuators with multiple wires receiving single pulses, or of a single wire receiving multiple pulses.

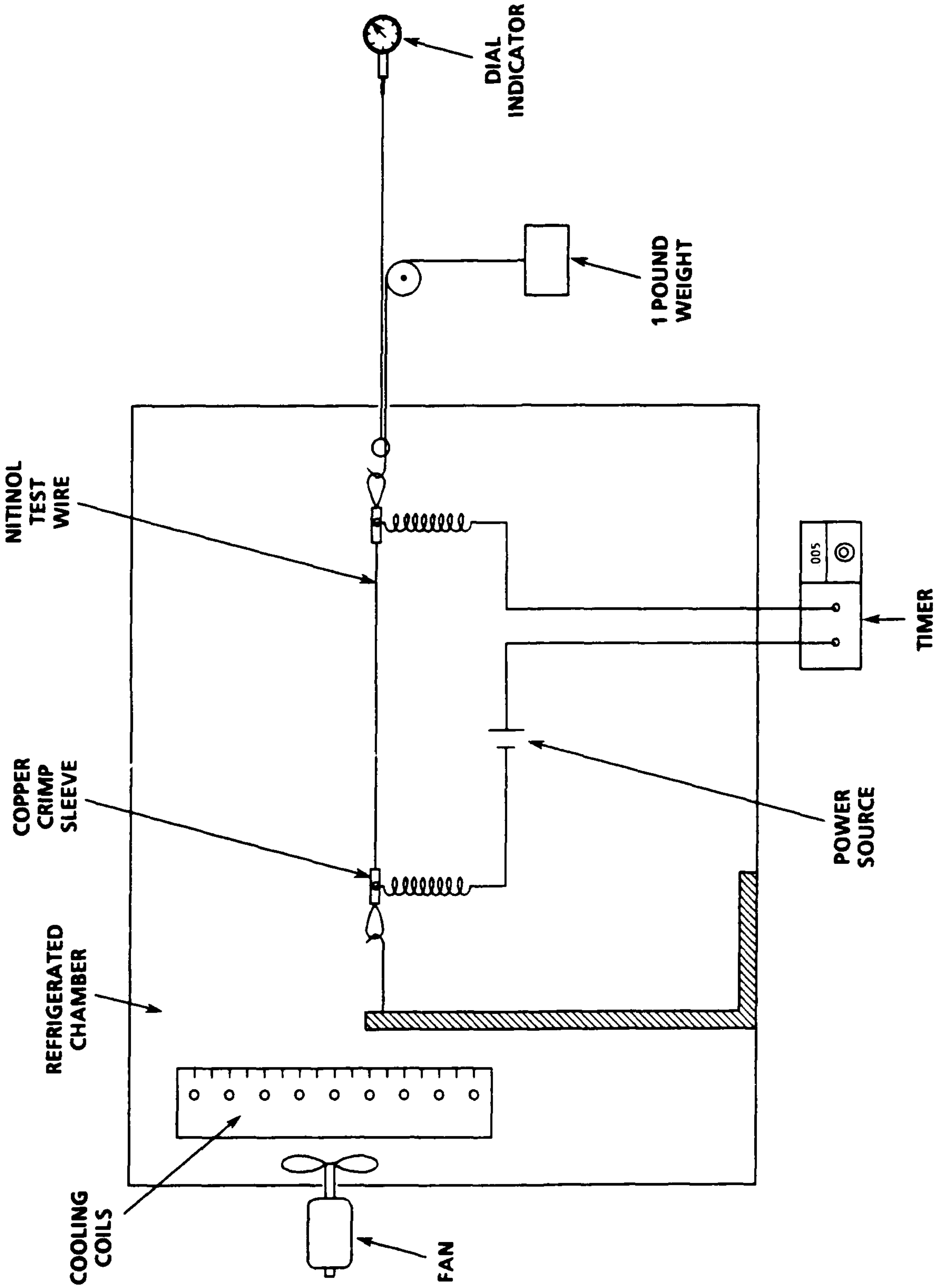

FIGURE 1. COLD CHAMBER TEST ARANGEMENT

TABLE 1. TRANSFORMATION OF NITINOL WITH STARTING AMBIENT OF -35°C

NOTES:

Heat 83825
Wire diameter 0.010 inch
Length ~8 inches

Lifting 1 pound load
Stress 12,500 psi

Specimen No.	Battery Type	No. of Batteries	Test Temperature (°C)	Potential (Volts)		Pulse Length (sec.)	NITINOL Contraction (in)
				Open Circuit	Closed Circuit		
1	Lithium Thionyl Chloride: "D" Size in Series	4	-35	14.70	4.5	0.5	0.4
2		4	-35	14.56	10.	0.5	0.5
4		4	-35	14.39	11.1	0.5	0.4
6		3	-35	11.01	8.6	0.5	0.35
7		3	-35	10.93	8.6	0.5	0.45
8		3	-35	10.81	9+	0.5	0.45
9		2	-35	7.36	5.5	1.0	0.2+
9		2	-35	7.22	6.32	1.5	0.47
9	Lithium Sulfur Dioxide: "AA" Size in Series	4	+20	11.88	4.8	1.0	0.5
10		4	-35	11.86	3.9	1.0	0.005
10	"AA" Size in Series/ Parallel	4	-36	6.06	1.9	1.0	0
10	"AA" Size in Series	4	+20	11.80	5.1	1.0	0.4
11	Lithium Thionyl Chloride: "AA" Size in Series	4	-36	14.79	0.08	1.0	0
11		4	-36	14.80	0.08	1.0	0
11	"AA" Size in Series/ Parallel	4	-36	7.38	0.19	1.5	0
12	Lithium Thionyl Chloride: in Series	3	-36	11.02	7.7	1.0	0.4
13		2	-36	7.18	5.9	1.5	0.4
14		2	-36	7.13	5.9	1.5	0.4

EXPERIMENTAL RESULTS AND OBSERVATIONS

PRELIMINARY TESTS

Four zinc-carbon standard #6 size ($2\frac{1}{2}$-inch diameter, 6-inch length), 1.5 volt batteries in series (6 volts) actuated a non-virgin wire in preliminary tests. The batteries were held at 19°C, and the wire, initially also at 19°C, was tested at sequentially decreasing temperatures to -35°C. The initial pulses were of two seconds duration, which lifted the 1-pound weight by 0.4 inch. Figure 2 shows that this pulse transformed the wire as its ambient temperature was decreased to 0°C, but increased time was required to achieve full contraction at temperatures below 0°C.

Contraction was observed as a rapid rotation of the cumulative movement indicator on the dial gauge. Full contraction was selected to be nominally 0.4 inch. The actual maximum contraction of a specific wire was a function of both its total energy input and its power input, i.e., the rate of energy input. Short, high power pulses heat the wire to a higher temperature than longer pulses of the same energy. The short, high power pulse produces the greater contraction.

The current flow in the test at -35°C (less than 2 amperes) offset the heat losses of the bare wire in the moving air environment and increased its temperature to about 100°C, producing transformation under load. However, the slope of the curve in Figure 2 suggests that pulse lengths of 6 seconds and a temperature of -35°C are the practical limits to operation for the specified test conditions.

Lithium polycarbon monofluoride batteries, which are not rated for sub-zero operation, were also tested.*

TESTS AT -35°C

Lithium thionyl chloride batteries have a high open circuit potential, 3.66 volts, and are rated for service at -35°C. Test data for NITINOL wires and these batteries, which were equilibrated at 35°C, are given in Table 1.

*Six "C" size lithium polycarbon monofluoride cells, in series and somewhat below room temperature fully contracted the same wire with a 0.5 second pulse. These partially discharged cells had an open circuit potential of 16.1 volts, falling to about 7.5 volts during pulsing. Five of these cells, when cooled to -35°C for 4 hours, produced about 50 percent contraction (0.180 inch) of the wire with a pulse of 2 seconds duration.

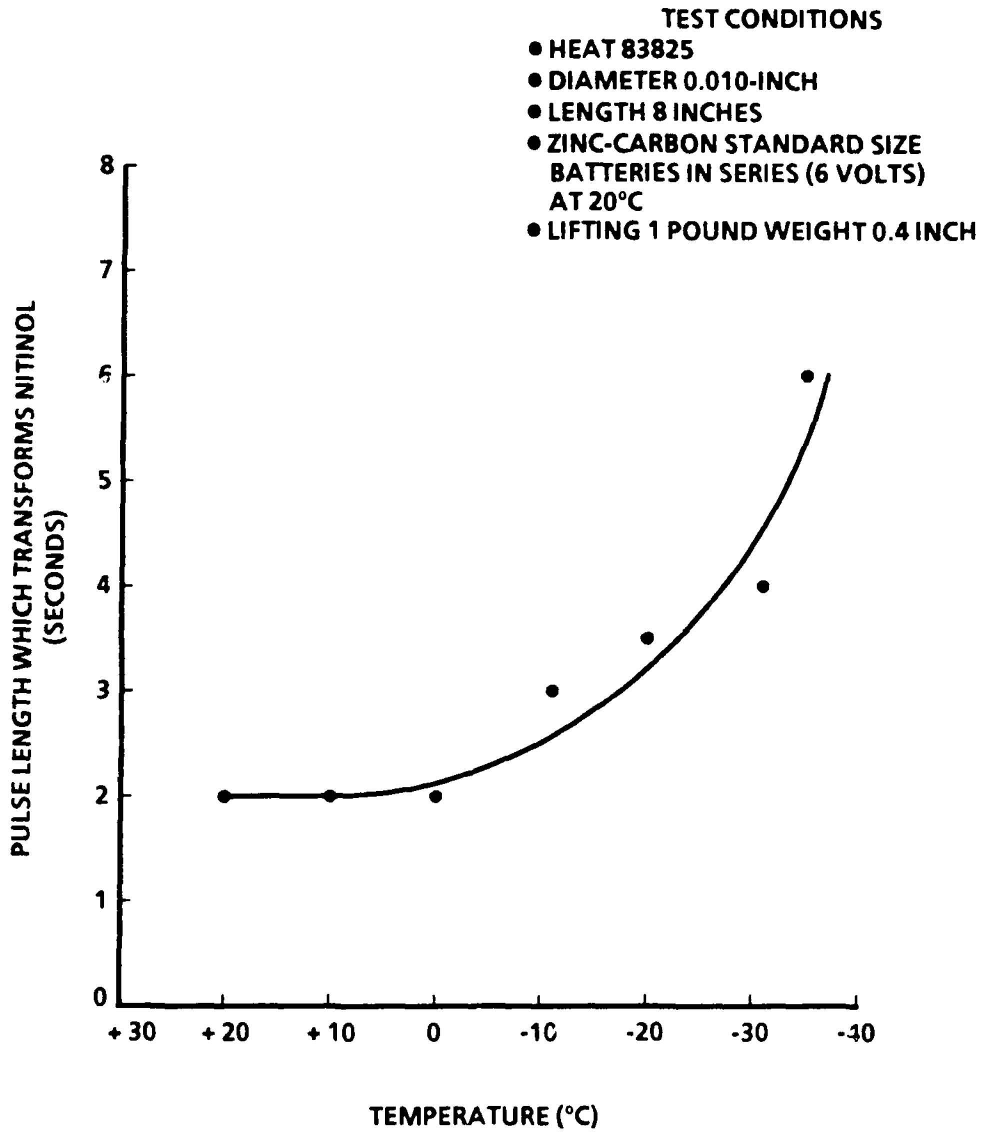

FIGURE 2. TRANSFORMATION OF NITINOL: PULSE DURATION VS AMBIENT STARTING TEMPERATURE

Specimens 1, 2, and 4 were tested with four "D" size batteries. These wires contracted extremely rapidly, jerking the load upward. The pulses of 0.5 seconds were clearly longer than required for transformation.

One battery was then removed from the circuit, reducing the open circuit voltage for tests of specimens 6, 7, and 8. The three batteries produced transformation under load. The 0.5-second pulses produced rapid contraction, but without the jerk seen in the prior tests.

Specimen 9 was tested with two batteries and a 1-second long pulse. This produced about 50 percent (0.2 inch) of full contraction of the wire, while a subsequent pulse of 1.5 seconds fully contracted the re-stretched wire.

Lithium sulfur dioxide cells are also rated for -35°C service. They retain a greater proportion of their room temperature open circuit voltage at -35°C than do lithium thionyl chloride cells, but their initial open circuit voltage is 2.95 vs. 3.6 volts for thionyl chloride. Four "AA" size sulfur dioxide batteries in series did contract the re-stretched specimen 9 when both wire and batteries were at 20°C. Thus it was known that four AA cells could sustain the requisite power long enough (one second) to transform the wire under load. The reserve capacity of the AA batteries is greatly diminished at -35°C, however, and consequently they were unable to raise the temperature of the virgin specimen 10 into the transformation range. Nor did using the four batteries in a series parallel circuit at -35°C produce a transformation. Rewarming the batteries (in series) and the wire to 20°C did contract the (still virgin) wire specimen 10. Thus, four AA size batteries are suitable for room temperature use, but not for -35°C service.

One other size lithium sulfur dioxide battery (U.S. Army BA 5567/U) was evaluated at -36°C. The result, not shown in Table 1, was non transformation of a virgin wire. The test consisted of four cells in series, 11.8 volts open circuit. The four cells have the diameter of a C cell and, when stacked, are about 40 percent longer than a single C cell.

Four AA size lithium thionyl chloride cells in series did not transform virgin specimen 11 in a pair of sequential tests at -36°C. Neither did series parallel circuitry produce transformation with a 1.5 second pulse.

"C" size lithium thionyl chloride batteries did transform virgin wires at -36°C. Specimen 12 was transformed with three batteries in series, while 13 and 14 were then sequentially transformed with only two of the three batteries. These latter three tests establish that the cold batteries functioned well for three sequential tests with virgin wires. The recovery of 97 percent of the initial open circuit voltage at -36°C, and the high closed circuit voltage shown in Table 1 indicate that the "C" size batteries are suitable replacements for the larger "D" size.

DISCUSSION

Data in the literature on NITINOL are inadequate for prediction of the performance of NITINOL under the described conditions. The test results reported here provide an approximation of the energy input and the work output of a simple NITINOL transducer operating at -35°C, along with its energy source. These data enable design of prototype actuating devices.

In these tests, non-equilibrium variables interplay and determine whether NITINOL can reach its transformation temperature. For example, during the energy input pulse, the resistance of the NITINOL is intrinsically changing in a peculiar way; the batteries are supplying energy at a decreasing rate (independently of the changing external resistance); and the wire is radiating heat to a moving air atmosphere.

Efficiency, based on the work output vs. energy input (typical closed circuit voltage, average resistance, and pulse time) is about 0.4 percent for the specified operating conditions. Transducer efficiency increases as the ambient temperature approaches the transformation temperature and less heat is used merely to bring the wire into the transformation range. (The actual latent heat of transformation of this NITINOL test specimen is about 2 joules, or 27 joules per gram.) Efficiency is of secondary significance in the context of applications for these devices.

Under the certain circumstances, cold batteries may deliver more power on their second or third pulse than on their first. This results from internal heating of the battery as it becomes part of a closed circuit, and its reserve power increases with its increasing internal temperature.

The shelf life of batteries is increased greatly by cold storage, enabling dormant batteries to be awakened for use by a short circuiting pulse. This phenomenon works to the natural advantage of NITINOL actuator concepts.

In warm ambient conditions, energy demands on batteries for actuation of NITINOL are decreased greatly due to the increased proximity of the ambient to the transformation temperature.

Optimizing NITINOL performance for a specific application should include consideration of variables such as diameter and length of the wire, heat treatment, and thermal insulation.

With respect to the energy source, a battery construction supporting a high current flow under short circuit conditions would perform best in this application. The readily available, commercial batteries used in the work were designed for long life with lower current draws. If high current flow batteries in either lithium sulfur dioxide or lithium thionyl chloride systems become available, they would be suitable

energy sources for low temperature operation, possibly with reduced volume as compared to those used in this work.

Viable activation of the arbitrarily selected 10 mil diameter wire was best achieved (specimens 13 and 14) using two "C" size lithium thionyl chloride batteries. Their volume is 3.23 cubic inches or, if placed in a box, 4.16 cubic inches. They weigh 0.23 pound, are non-magnetic, and do operate repetitively at -35°C.

Given the substantial work performed by the very small volume of a NITINOL wire, useful activating devices probably can be designed in packages of less than 6 cubic inches, including batteries. Since NITINOL alloys are used in Naval ships and aircraft, fewer qualification procedures are needed for new applications. The alloy is non-magnetic and resistant to marine corrosion.

CONCLUSIONS

At -35°C, two "C" lithium thionyl chloride batteries will activate a stretched 10 mil diameter, 8-inch long NITINOL wire within a -35°C moving air environment. The activated wire will lift a 1-pound load a minimum of 0.4 inch, exerting a stress of 12.7 ksi.

An activating device based on NITINOL wire, designed to operate effectively in a frigid environment, can probably be packaged within 6 cubic inches, including batteries.

RECOMMENDATIONS

It is recommended that several actuator modules be constructed to demonstrate the capabilities of these transducers to potential users. The special attributes of these devices include a non-magnetic signature, no significant magnetic or electrical spike, noiseless operation, minimum weight and volume, time delay capability, all weather operation, fail-safe capability, conflagration safing, low cost, and high reliability. These attributes warrant the continued research of this electronically controlled, electrically energized NITINOL actuator.

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